# Star, a New Concept in Robotics



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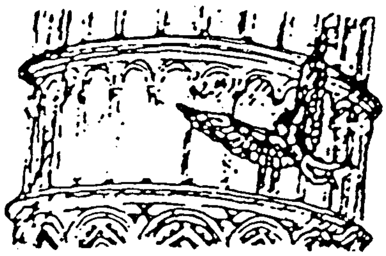

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# STAR, A NEW CONCEPT IN ROBOTICS

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ABSTRACT

Our aim is to apply the Group Theory to the structural design of manipulator robots and to obtain kinematic equations with ease and rapidity. We will concentrate our attention on parallel manipulator robots and in particular those capable of only spatial translation. An entire family of robots results from our investigation. The Y-STAR manipulator presented in this paper has been studied and chosen as a representative for its interesting characteristics. A prototype was constructed at the Ecole Centrale Paris and a video simulation of the robot at work was also produced. Y-STAR responds to the increasing demand of fast working rhythms in modern production and is suited for any kind of pick and place jobs like sorting, arranging on palettes, packaging and assembly.

INTRODUCTION

The mathematical Group Theory and more precisely Lie Group Theory has proved to be a useful tool to model displacements of a rigid body [ 1 ], [ 2 ],[ 3 ],[ 4 ],[ 5 ],[ 6 ],[ 7 ],[ 8 ],[ 9 ]. If we call { D } the set of all possible displacements, we can easily verify that it has a group structure, i.e. the four following properties hold: (1) closure under composition, (2) association, (3) the existence of an identity, (4) the existence of an inverse. Hence all the theorems of the Group Theory can be used to establish the mechanical properties of mechanisms.

MECHANICAL LIAISONS

A kinematic chain is a finite set of rigid bodies, a certain number of which are coupled in kinematic pairs. The coupling between two rigid bodies of any kinematic chain generates a set of permitted relative movements which is represented by a subset of the displacement group { D }. Such a generalization of the kinematic pairs is referred to as a mechanical liaison. An exhausive inventory of the displacement subgroups has been established [2].

Composition of Liaisons
The putting in series physically of kinematic pairs is mathematically expressed by the composition product of the operators representing the component liaisons. By applying composition laws we can build simple open chains which correspond to the serial manipulator robots.
Because of the definition axioms of a group, the composition product of elements of a given displacement subgroup is a member of the same subgroup. Therefore, if two component liaisons are two subsets of a given subgroup, the composition liaison is also a subset of this subgroup. The subset may be a subgroup itself or not.

Intersection of Liaisons
If we join two bodies by two mechanisms, we can say we have two parallel liaisons between the bodies. Their relative movements are then governed at the same time by the two liaisons, that is to say by the intersection liaison. Doing so, we produced a new mechanical liaison which is represented by the intersection set of the two sets of operators associated to each parallel liaison.
In order to generate spatial translation with parallel mechanisms, we are led to look for displacement subgroups the intersection of which is the spatial translation subgroup { T }. We will consider only the cases for which the intersection subgroup is strictly included in the two "parallel" subgroups. The most important case of this sort is the parallel association of two { X(w) } subgroups with two distinct vector directions w and w'. It is easy to prove :

$$\{ X(\mathbf{w}) \} \cap \{ X(\mathbf{w}') \} = \{ T \} \qquad \mathbf{w} \neq \mathbf{w}'$$

THE { X(w) } SUBGROUP

The subgroup { X(w) } plays a prominent role in

mechanism design. This subgroup combines spatial translation with rotation about a movable axis which remains parallel to a given direction w (fig.1). Physical implementations of { X(w) } mechanical liaisons can be obtained by putting in series kinematic pairs represented by subgroups of { X(w) }. Practically only primatic, revolute and screw pairs P, R, H are used to build robots ( the cylindric pair C combines in a compact way a prismatic pair and a revolute pair). A complete list of all possible combinations of these kinematic pairs generating the { X(w) } subgroup is given in [10]. Two geometrical conditions have to be satisfied in the series : the rotation axes and the screw axes are parallel to the given vector w ; there is no passive mobility.

The displacement operator for the { X(w) } subgroup, acting on point M is :

$$M \rightarrow N + au + bv + cw + \exp( hw \wedge )NM$$

Point N and the vectors **u**, **v**, **w** make up an orthogonal frame of reference in the space and a, b, c, h are the four parameters of the subgroup which has dimension 4 .

We recall that a displacement operator is a geometrical transformation acting on points M in the space $\mathcal{E}$ (euclidean affine space of dimension 3) such that the length of the vectors and the orientation of the angles are mantained. Thus, if a displacement operator acts on the points of a rigid body, it gives these points for a new position of the same body. The advantage of using this method to find mathematical expressions is that it is independent of the choice of a particular frame of reference.

PARALLEL ROBOTS FOR SPATIAL TRANSLATION

To produce spatial translation it is sufficient to place two mechanical generators of the subgroups { X(w) } and { X(w') } , w ≠ w', in parallel, between a mobile platform and a fixed platform. If we want to build a robot which has only fixed motors then three generators of the three subgroups { X(w) } , { X(w') } , { X(w'') } , w ≠ w', w' ≠ w'', w'' ≠ w, are needed. Any series of P, R or H pairs which constitute a mechanical generator of the { X(w) } subgroup can be implemented. Moreover, these three mechanical generators may be different or the same depending on the desired kinematic results. This wide range of combinations gives rise to an entire family of robots capable of spatial translation. Simulation of the most interesting architectures can easily be achieved and the choice of the robot to be constructed can therefore meet the needs of the commissioner. Clavel's Delta robot belongs to this family as it is based on the same kinematic principles [11], [12].

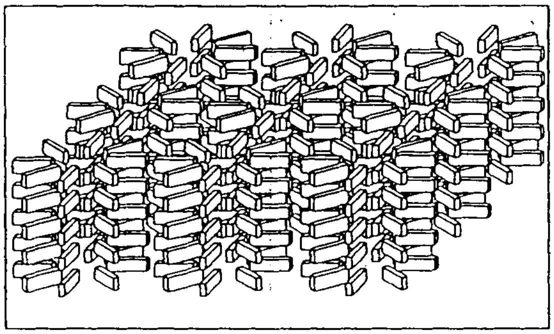

fig.1

THE PARALLEL MANIPULATOR Y-STAR

STAR is made up by three cooperating arms which generate the subgroups { X(**u**) } , { X(**u'**) }, { X(**u''**) } (fig. 2). The three arms are identical and each one generates a subgroup { X(**u**) } by the series RHPaR where Pa represents the circular translation liaison determined by the two opposite bars of a plane hinged parallelogram.

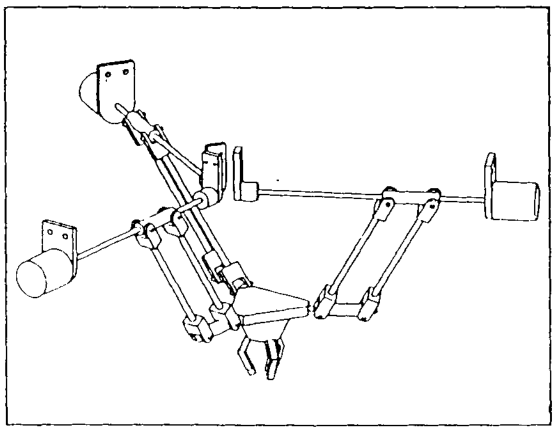

fig.2

The axes of the two revolute pairs and of the screw pair must be parallel in order to generate a { X(u) } subgroup. Hence we write R1**u**H**u**PaR2**u**. For each arm, the first two pairs, i.e. the coaxial revolute pair and the screw pair, constitute the fixed part of the robot and form at the same time the mechanical structure of an electric jack which can be fixed in

the frame. All the Hu axes lie on the same plane $\Pi$ and divide it into three identical parts thus forming a Y shape. Hence the angle between any two axes is always $2\pi/3$. The mobile part of the robot is made up by the PaR2u series of each arm that all converge to a common point below which the mobile platform is located. The platform stays parallel to the reference plane $\Pi$ and cannot rotate about the axis perpendicular to this plane. Any kind of appropiate end effector can be placed on this mobile platform. In this particular architecture of the robot we chose to have deformable parallelograms to produce translation. Indeed, the two opposite bars of a parallelogram are coupled by a one-degree-of-freedom mechanical liaison of circular translation. Each bar moves relative to the other describing equal circles. Circular translation liaisons constitute a non-empty subset (or complex) of dimension 1 (1 degree of freedom) of the subgroup { T(P) } of plane translations parallel to a given plane P. The three deformable parallelograms ensure the stability and increase the rigidity of the whole. As we have already mentioned above, the axis of the last revolute pair R2u has to be parallel to the one of the first revolute pair R1u. This theoretical condition needs to be carefully applied in practice.

## DERIVATION OF THE { T } SUBGROUP

To express the kinematic transformations of any given point M of the mobile platform bearing the end effector, we shall use the direct intrinsic vector method. We shall consider only two arms, as the two subgroups { X(**u**) } and { X(**u'**) } are sufficient to produce the intersection subgroup { T }. As a first step, we shall cut the platform in two parts allowing independent operations of the two "parallel" arms. For the first arm we observe that each component pair permits only one degree of freedom represented by an angle that we shall put into brackets i.e. $R1u(\varphi)Hu(\chi)Pa(\vartheta)R2u(\psi)$. For the second arm we will therefore have: $R1\mathbf{u}'(\varphi')H\mathbf{u}'(\chi')Pa(\vartheta')R2\mathbf{u}'(\psi')$.

The first step of the direct intrinsic vector method is to describe the initial configuration. Easy computation can be obtained by choosing a particular configuration. In this case, we have the arms in a vertical initial configuration (fig. 3).

(**u**,**v**,**w**) make up a direct orthogonal vector base. C is the center of the mobile platform, M is any point belonging to the same platform and O is the point common to the three axes.

CB = Cu and AB = bw.

For technical reasons, in the practical implementation of the robot we should have c as small as possible whereas b, the arm's length, is a parameter which can be optimized depending from the desired application and the consequent working volume.

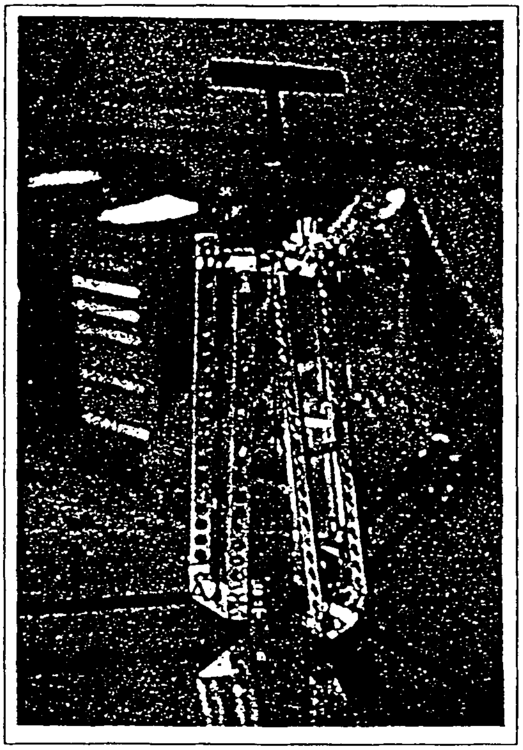

fig.3

In synthesis we have:

| | |
|---|---|
| revolute pair R1 | { axis O, **u** ≈ A, **u**<br>{ angle $\varphi$ |
| screw pair H | { axis O, **u** ≈ A, **u**<br>{ angle $\chi$, pitch $p=2k\pi$ |
| parallelogram Pa pair | { circles of radius b<br>{ angle $\vartheta$ |
| revolute pair R2 | { axis C, **u** ≈ B, **u**<br>{ angle $\psi$ |

We observe that the R1H pairs form the cylindric pair C. Hence we can consider our arm of the type CPaR. If we call $\alpha = \varphi + \vartheta$ we can write our { X(u) } generator as : $Cu(\alpha)Pa(\vartheta)Ru(\psi)$.

In this second step, we will establish the symbolic model of our mechanism using the previous system

of notation. For the first arm we have point M becoming M1' according to the formula :

$$\begin{bmatrix} \mathbf{AM_1'} \\ 1 \end{bmatrix} = \begin{bmatrix} \exp(\varphi \mathbf{u}\Lambda) & \mathbf{0} \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} \exp(\chi \mathbf{u}\Lambda) & k\chi\mathbf{u} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & b\cos\vartheta\mathbf{w} + b\sin\vartheta\mathbf{u} \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} \exp(\psi \mathbf{u}\Lambda) & \mathbf{0} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{BM} \\ 1 \end{bmatrix}$$

We notice that : $b\cos\vartheta\mathbf{w} + b\sin\vartheta\mathbf{u} = \mathbf{AB}$
and that: $\mathbf{BM} = \mathbf{BC} + \mathbf{CM} = c\mathbf{u} + \mathbf{CM}$.

$\mathbf{AM_1'} = \exp(\varphi\mathbf{u}\Lambda) \; \{k\chi\mathbf{u} + \exp(\chi\mathbf{u}\Lambda) [\exp(\psi\mathbf{u}\Lambda)\mathbf{BM} + b\cos\vartheta\mathbf{w} + b\sin\vartheta\mathbf{u}\,]\,\}$

After some calculations we obtain :
$\mathbf{AM_1'} = (\,c + k\chi + b\sin\vartheta)\mathbf{u} - (b\sin\alpha\cos\vartheta)\mathbf{v} + (b\cos\alpha\cos\vartheta)\mathbf{w} + \exp[(\varphi+\chi+\psi)\,\mathbf{u}\Lambda\,]\mathbf{CM}$.

In the vertical initial configuration we have that the projection of point C, center of the mobile platform, on the plane of the axes $\Pi$, is exactly point O, which is the point common to the three fixed axes. Hence :

$\mathbf{AO} = \mathbf{BC} = c\mathbf{u}$ and :
$\mathbf{AM_1'} = \mathbf{AO} + \mathbf{OM_1'} = c\mathbf{u} + \mathbf{OM_1'}$.

We finally obtain for the first arm :
$\mathbf{OM_1'} = (k\chi + b\sin\vartheta)\mathbf{u} - (b\sin\alpha\cos\vartheta)\mathbf{v} + (b\cos\alpha\cos\vartheta)\mathbf{w} + \exp[(\varphi+\chi+\psi)\,\mathbf{u}\Lambda]\mathbf{CM}$(1).

Analogous calculations for the second arm lead to the transformation $M \rightarrow M_2'$.
If we call $(\mathbf{u}',\mathbf{v}',\mathbf{w}')$ the direct orthogonal vector base associated to the second arm we observe that we can move from one base to another by the transformations :

$$\begin{cases} \exp(\,\delta\,\mathbf{w}\Lambda\,)\,\mathbf{u} = \sin\delta\,\mathbf{v} + \cos\delta\,\mathbf{u} = \mathbf{u}' \\ \exp(\,\delta\,\mathbf{w}\Lambda\,)\,\mathbf{v} = -\sin\delta\,\mathbf{u} + \cos\delta\,\mathbf{v} = \mathbf{v}' \\ \exp(\,\delta\,\mathbf{w}\Lambda\,)\,\mathbf{w} = \mathbf{w} = \mathbf{w}' \end{cases} \quad (2)$$

where $\delta$ is the angle formed by $\mathbf{u}$ and $\mathbf{u}'$.

So for the second arm we have :

$\mathbf{OM_2'} = [(k\chi' + b\sin\vartheta')\cos\delta + b\sin\alpha'\cos\vartheta'\sin\delta]\mathbf{u} + [(k\chi' + b\sin\vartheta')\sin\delta - b\sin\alpha'\cos\vartheta'\cos\delta]\mathbf{v} + b\cos\alpha'\cos\vartheta'\mathbf{w} + \exp[(\varphi'+\chi'+\psi')\mathbf{u}'\Lambda]\mathbf{CM}$.

As a matter of fact there is no cut in the mobile platform :

$\mathbf{OM_1'} = \mathbf{OM_2'}$ for any point M.

This means :

$$k\chi + b\sin\vartheta = (k\chi' + b\sin\vartheta')\cos\delta + b\sin\alpha'\cos\vartheta'\sin\delta \quad (3)$$
$$-b\sin\alpha\cos\vartheta = (k\chi' + b\sin\vartheta')\sin\delta - b\sin\alpha'\cos\vartheta'\cos\delta \quad (4)$$
$$b\cos\alpha\cos\vartheta = b\cos\alpha'\cos\vartheta' \quad (5)$$

$$\exp[(\,\varphi + \chi + \psi\,)\,\mathbf{u}\Lambda\,]\,\mathbf{CM} = \mathrm{I}$$
$$\exp[(\,\varphi' + \chi' + \psi'\,)\,\mathbf{u}'\Lambda\,]\,\mathbf{CM} = \mathrm{I} \quad \Rightarrow$$

$$\varphi + \chi + \psi = 2n\pi \quad (6)$$
$$\varphi' + \chi' + \psi' = 2n'\pi \quad (7)$$

We have 5 scalar equations for the 8 parameters $\varphi, \chi, \vartheta, \psi, \varphi', \chi', \vartheta', \psi'$. Thus only 3 parameters are free.
The last two equations show the absence of rotation for the mobile platform.
Obviously, all points of the platform have equal trajectories.

## INVERSE KINEMATICS

Equation (1) gives the coordinates x, y, z of point C as a function of the parameters and of the linear displacement coordinate of point A along its axis :

$A \rightarrow A'$ , so that : $\mathbf{AA'} = d\,\mathbf{u} = k\chi\mathbf{u}$.

$$\begin{cases} x = d + b\sin\vartheta \\ y = -b\cos\vartheta\sin\alpha \\ z = b\cos\vartheta\cos\alpha \end{cases}$$

With the help of the above equations, we can easily find the linear displacement that each screw has to accomplish in order to obtain the desired (x, y, z) position of the center of the mobile platform.

$$b^2\sin^2\vartheta = (x-d)^2 = b^2 - b^2\cos^2\vartheta = b^2 - (y^2 + z^2).$$

But $0 \leq \vartheta \leq -\pi/2$ so that: $\sin\vartheta = \sqrt{b^2 - (y^2+z^2)}$
therefore $d = x + \sqrt{b^2 - (y^2 + z^2)}$ .

As from previous calculations for the second arm we obtain :

$d' = x' + \sqrt{b^2 - (y'^2 + z'^2)}$ and in general :

$$d_i = x_i + \sqrt{b^2 - (y_i^{\,2} + z_i^{\,2})} \qquad i = 1,2,3.$$

Recalling the transformations (2) we obtain the formula :

$$\boxed{\begin{array}{l} d_i = x \cos\delta_i + y \sin\delta_i + \\ \sqrt{b^2 - x^2 - y^2 - z^2 + (x \cos\delta_i + y \sin\delta_i)} \\ i=1,2,3. \end{array}}$$

For the symmetric position of the three axes on the fixed plane, we have :

$\delta_1 = 0$ ; $\delta_2 = 2\pi/3$ ; $\delta_3 = -2\pi/3$ so that :

$$\begin{cases} d_1 = x + \sqrt{b^2 - (y^2 + z^2)} \\ d_2 = -(1/2)\, x + (\sqrt{3}/2)\, y + \\ \quad \sqrt{b^2 - (z^2 + (3/4)\, x^2 + (1/4)\, y^2 + (\sqrt{3}/2)\, x\, y)} \\ d_3 = -(1/2)\, x - (\sqrt{3}/2)\, y + \\ \quad \sqrt{b^2 - (z^2 + (3/4)\, x^2 + (1/4)\, y^2 - (\sqrt{3}/2)\, x\, y)}. \end{cases}$$

We can affirm that, in a first approximation, the angle about which each screw has to turn in order to reach the desired position (x, y, z) of the center of the platform is :

$\chi_i = d_i / k$ , where k is the pitch of the screw axis.

However, to obtain the maximum precision, we should also take into account the rotation of the deformable parallelograms about the **u** axis. We call $\beta$ the angle formed by the vertical to the **u** axis and the **AB** vector in the **vw** plane, from **w** towards **v**.

If we consider only the two possible rotations of the deformable parallelogram without any linear displacement of point A along the fixed axis, we can write :

$$\begin{cases} x_i = d_i + b \sin\vartheta_i \\ y_i = -b \cos\vartheta_i \sin\beta_i \qquad i = 1,2,3 \quad \Rightarrow \\ z_i = b \cos\vartheta_i \cos\beta_i = z . \end{cases}$$

$$\cos\beta_i = \frac{z}{\sqrt{b^2 - (x_i - d_i)^2}}$$

and with the help of the previous calculations, we obtain the formula :

$$\beta_i = \arccos \frac{z}{\sqrt{x^2 + y^2 + z^2 - (x \cos\delta_i + y \sin\delta_i)^2}}$$

For a long pitch, as the one we chose in the physical implementation of the STAR robot, that is 50,8 mm, this formula may lead to a correction of the screws' linear displacement of 12,7 mm, which is of absolute relevance due to the hyperstatic nature of the mechanical structure.

The complete inverse kinematic formula is then :

$$\boxed{\begin{array}{l} d_i = x \cos\delta_i + y \sin\delta_i + \\ + \sqrt{b^2 - x^2 - y^2 - z^2 + (x \cos\delta_i + y \sin\delta_i)} \\ - \arccos \dfrac{z}{\sqrt{x^2 + y^2 + z^2 - (x \cos\delta_i + y \sin\delta_i)}} \\ i = 1,2,3. \end{array}}$$

## TEST AND SIMULATION

A 3-dimensional video simulation of STAR at work was produced. It shows our robot assembling some small toy cars on a production line at fast working rhythms. Moreover, a simpler software simulation was developped to test our calculations and visualize some trajectories (fig.4).

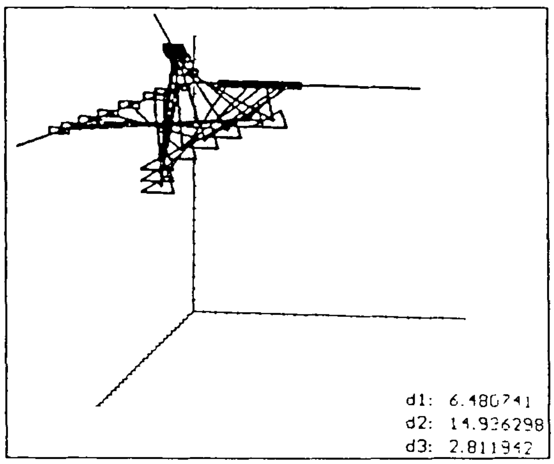


fig.4

This software was written in C++ and can also be used to optimise the relative position of the fixed axes : the U and T configurations are being studied. Another simulation was carried out on a spreadsheet using the arm's length and the angles between the axes as parameters. This simulation lets us observe that when we work in the vicinity of the boundary of the working volume, considerable linear displacements of the screws are necessary to produce a relative small movement of the mobile platform compatible with the mechanical structure.

It is then preferable to work in the central part of the working volume in order to obtain the maximum precision. The spreadsheet's calculations can also be used to optimise the arm's length as a function of the working volume. For example it is not possible to reach positions (103,50,0) or (100,220,0) with b= 600 mm.

SINGULAR CONFIGURATIONS

The research of singular configurations is quite important. In fact, in this case the mobile platform would be displaced without any movement of the actuators and the whole mechanism would not be under control any more [13] . In addition, in the vicinity of a singular configuration, articular forces may be considerable.
After many calculations, done also with the help of some software, only the two obvious singular configurations have been found :

(1) $z=0$, $x=b$, $y=b$ ; (2) $z=b$, $x=0$, $y=0$.

The determinant of the inverse jacobian matrix is zero only in some other points situated on the border of the working volume but not inside it.

THE WORKING VOLUME

Y-STAR robot's working volume can be represented as the intersection of three volumes (V) isometric by a rotation of 120°. The rotation axis (R) and one of these volumes (V) are drawn in fig. 5

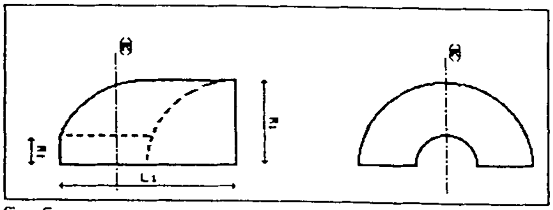

fig.5

The volume accessible by a single arm of the robot is an hemi-cylinder of radius $R_{a1}$ equal to the arm's length and height equal to the axis' length. We add to this the half of a sphere of radius $R_{a1}$ on both sides. However, a thinner cylinder of radius $R_{a2}$ has to be cut off from the previous volume. In doing so, we take into account the limit angle $\vartheta_l$ due to the physical links between the mechanical components of the robot. The angle $\vartheta$ between the axis and the arm has to be $\vartheta_l \leq \vartheta \leq 90°$ for the architecture of the global system (fig. 6). We have then to remove half a sphere of radius $R_{a1}$ at the end of each cylinder, opposite to the common center of the fixed axes. We obtain therefore the volume (V) shown in fig. 7.

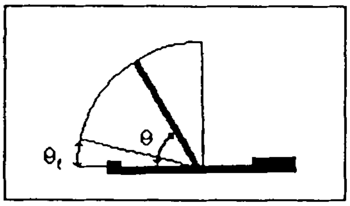

fig. 6

The physical implementation of the robot we built has the following dimensions :
$R_{a1} = b = 500$ mm; $R_{a2} = 44$ mm; $L_1 = 600$ mm.

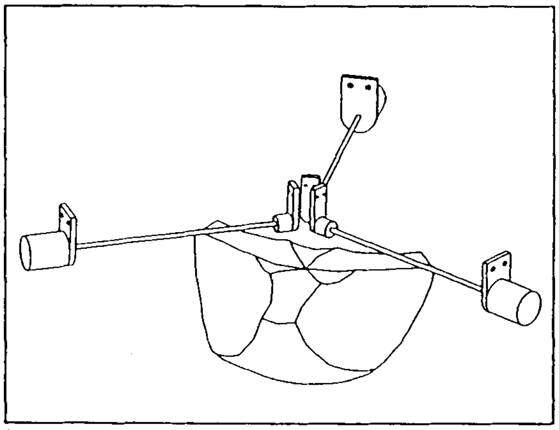

fig. 7

One can think that the longer the arms, the greater the working volume. However if we take an axis' length of 600 mm, this is true up to 400 mm. For example for a 750 mm arm's length the working volume is very little. The parameter to be considered is then the ratio between the arm's length and the fixed axis' length.
Always working with an axis of 600 mm long we observed that from a 300 mm arm's length up, the horizontal sections of the base of the working volume take the form of a star with 3 branches which get thinner and thinner as the length of the arm increases. We concluded that the ideal ratio ranges from 1/2 to 2/3. This means in our case b = 350 to 400 mm. Our choice of having an arm 500 mm long may be justified for example by security reasons : we obtain a relatively thin working area at the bottom and we mechanically restrict the access of the robot to certain positions in the space.

## PHYSICAL IMPLEMENTATION : STAR IS A REALITY

A small prototype was built at the Ecole Centrale Paris by Professor's Hervé research team (fig. 8, 9, 10). It is made of alluminium alloy (durall) and has the following parameters : b=500 mm = arm's length; l=600 mm= fixed axis' length ; k=50,8 mm = screw's pitch. Further tests will be carried out on this prototype to determine its characteristics and performances [14].

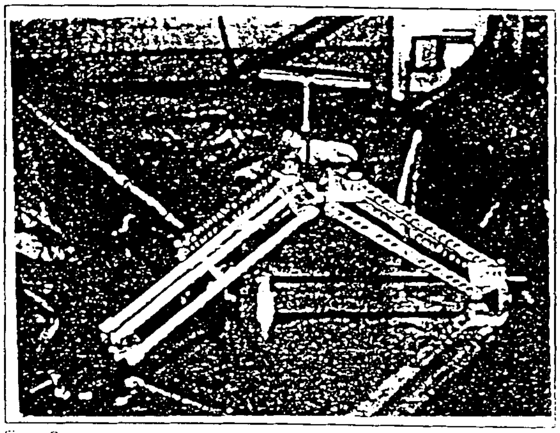

fig. 8

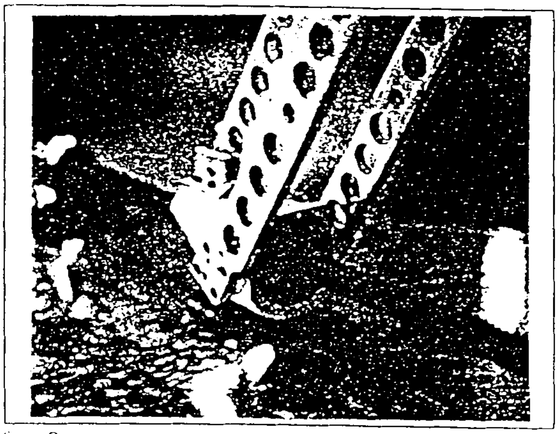

fig. 9

## FUTURE IMPROVEMENTS

Future improvements concerning the global mechanical structure may be achieved by studying the working volume and the inverse kinematic problem of the other robots belonging to the same family as Y STAR. Appropiate software is being developped to simulate the different options and could constitute in the future a useful tool to help industrialists choose the version of the parallel robot which best suits their needs.

Technical improvements can also be implemented : for example a second screw pair having the same pitch as the first may replace the second revolute pair R2 (fig11). No correction of the positionning angle would then be necessary.

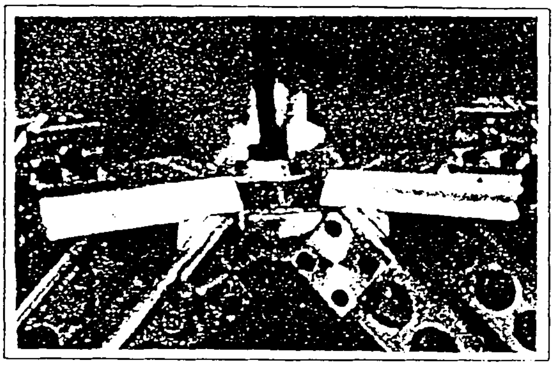

fig. 10

The choice of composite matrerials for the arms and the mobile platform will of course improve the efficiency of the device. However, the cost of constructing such a prototype can be afforded only with the collaboration of an industrial partner. A study of control using transputers will be done in the near future.

## CONCLUSIONS

Group Theory is a powerful tool for designing parallel link mechanisms for robots. Nevertheless, investigation of new parallel robots generating pure translation is only at its beginning. Parallel robots are a solution when the rigidity is of more importance than the size of the working area. In addition, increasing performances and the low cost of fabrication make them attractive for modern industry. The new robot Y-STAR is presented as an alternative to the DELTA robot. It has the classical parallel robot advantages for positioning, precision, rapidity and fixed motor location. Moreover it can be produced in different versions and materials. Optimisation is currently being studied and considerable improvements may come from the implementation of electronic control.

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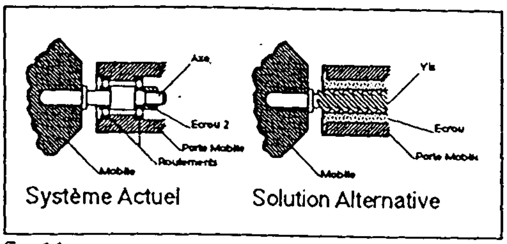


fig.11

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